MICROGRAVITY SMOLDERING COMBUSTION EXPERIMENTS IN THE SPACE SHUTTLE

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INTRODUCTION

Smoldering combustion poses a substantial fire risk both here on earth and in spacecraft. Despite the flow restriction caused by the presence of the porous material, smoldering combustion has been shown to be influenced by buoyancy[1]. These buoyant effects have been the subject of a microgravity research program titled the Microgravity Smoldering Combustion (MSC) experiment. In prior papers, two opposed forced-flow tests have been reported [1]. This paper presents results of an additional opposed-flow test obtained on STS-105 (August 2001) and presents new results from ground-based testing and analysis. In forced flow smolder experiments, the ambient pressure in the MSC chamber rises, thus motivating the need to understand the effects of pressure on smoldering combustion. These tests are compared with data obtained from experiments conducted aboard the Space Shuttle in flights STS-69, STS-77, and STS-105. Measurements of one-dimensional smolder propagation velocity are made by thermocouple probing and a non-intrusive Ultrasound Imaging System (UIS) [2,3,4]. Thermocouples are also used to obtain reaction temperatures and the UIS is used to determine instantaneous variation of the fuel permeability due to the progress of the smolder reaction.

EXPERIMENTAL HARDWARE AND PROTOCOL

Ground-based and microgravity tests were conducted in identical MSC flight hardware on 120mm diameter and 150mm length cylindrical samples of open-cell, unretarded, polyurethane foam [1]. The tests were conducted in two configurations: opposed forced flow in microgravity and opposed forced flow in normal gravity (downward). A constant oxidizer mass-flux was delivered by choked orifices (microgravity) or a mass flow controller (normal gravity). The sample was enclosed in a 21-liter chamber thus the ambient pressure rose throughout the test. For the first two flights and the comparable ground tests, the foam sample was enclosed in a 3 mm thick quartz cylinder. For STS-105 (and the ground-based testing), the quartz cylinder was replaced with a 5 mm thick Vespel ™ cylinder to allow access for the UIS diagnostic. For the STS-105 test and the associated ground tests, the igniter power was reduced. The hardware is described in more detail in other papers [1,5].

BACKGROUND

Smolder often occurs under oxygen-limited conditions [6], and consequently, the rate of heat release from the smolder reaction is directly proportional to the oxidizer mass flux. Away from extinction conditions, the smolder propagation velocity is then proportional to the heat release rate minus heat losses to the environment [7]. In low-gravity, pressure change has little effect on the oxidizer mass flux. However, in the presence of gravity, the buoyant velocity is strongly influenced by the pressure. With buoyancy as the driving force, the pressure gradient along the length of the cylindrical sample can be written as $dP/dz = -\rho g$. For a flow in a porous medium Darcy's Law is applicable [8] $dP/dz = -(\mu/K)u_D$ and equating these two gives an estimate of the buoyant flow velocity, u_D, through the medium. The resulting oxidizer mass flux is $\dot{m}''_{O_2,Buoyant} = y_{O_2}\rho_{air}u_D = y_{O_2}(\rho_{air})^2 gK/\mu$. A calculation of the buoyancy-induced oxidizer mass flux is conducted based on data from the natural convection tests. It has been observed via the UIS that permeability changes with the passage of the smolder propagation front and the final char permeability increases with increasing oxidizer mass flux [2,9]. An increased oxidizer mass flux leads to a more vigorous reaction, which consumes more fuel, and leads to a higher permeability of the residual char. In normal gravity tests, increased pressure leads to increased buoyancy-induced oxidizer mass flux, and consequently to an increased permeability.

The pressure effects on diffusive transport of heat and mass are determined by examining the effects of pressure on the binary diffusion coefficient. The diffusive mass flux is given by $\dot{m}''_{O_2,Diffusive} = \rho D \nabla y_{O_2}$. The binary diffusion coefficient is proportional to $T^{1.5}/P$ [10]. Thus, it is expected that the diffusive mass flux is relatively independent of the pressure insomuch as the reaction temperatures are not significantly changed over the range of pressures tested.

The forced oxidizer mass flux is given by $\dot{m}"_{O_2,Forced} = y_{O_2}\rho_{air}u_{forced}$. In the present experiments the mass flux is controlled through the MFC, and therefore is independent of pressure. The total oxidizer mass-flux is the sum of oxidizer mass fluxes from buoyancy-induced flow, diffusive transport, and controlled forced flow. The total oxidizer mass-flux is therefore expressed as:

$$\dot{m}"_{O_2,Total} = \frac{y_{O_2}\left(\rho_{air}\right)^2 gK}{\mu} + \rho_{air}D\nabla y_{O_2} + \dot{m}"_{O_2,Forced} \tag{1}$$

Concerning the heat losses to the environment, an analysis of free convection on the outside of the sample cylinder indicates that heat losses, described in terms of the Nusselt number, are proportional to the Rayleigh number to the power of ¼. Since the Rayleigh number is proportional to the square of the pressure, then the heat losses from the smoldering sample are expected to rise as $P^{1/2}$ [11].

For an oxygen-limited reaction, the heat release rate, from the propagating smolder reaction, can be estimated by multiplying the oxidizer mass flux by the heat of smolder combustion (per unit mass of oxidizer). The effect of pressure on the heat of smolder combustion is not well known, although since the heat of combustion depends on the products of combustion it should depend on the characteristics of the smolder reaction. The effect of pressure on heterogeneous reaction chemistry is difficult to quantify, but assuming that the reaction rate behaves as an Arrhenius reaction of first order in oxidizer, then the reaction rate should be proportional to pressure [12]. Thus it could be inferred that the rate of heat release would be proportional to pressure, approximately to the ½ power.

RESULTS & DISCUSSION

The microgravity test results are summarized in Table 1. The smolder velocity (from the thermocouples) increases with the forced oxidizer flow rate. For the 3 mm/s case, the smolder velocity was also obtained by the UIS, the measured value (0.18) is in excellent agreement with the value obtained from the thermocouples. Figure 1 presents the temperature profiles for the 3 mm/s case, typical of opposed flow tests, the profiles all approach the same peak value and then decrease as the reaction front passes. The smolder velocity can be deduced from these measurements, by tracking the time for each location to reach the smolder temperature. Figure 2 present the UIS results for the same test, the permeability can be seen to increase progressively as the front passed each sensor.

Using the measured permeability and equation 1, the total mass flux of oxygen can be calculated for normal gravity tests, facilitating comparison with the microgravity tests. To provide flow rates that span the desired range, a series of tests were conducted (for natural convection and forced flow) at a variety of ambient pressures. These results are plotted in Figure 3 with the low-gravity results. Using Equation 1 to examine the effect of pressure change on the microgravity results the smolder propagation velocity was observed to be only slightly affected by pressure. Since the mass flux of oxidizer is constant, this indicates that there is only weak dependence on pressure on the smolder propagation rate. This substantiates the use of equation 1 and pressure variation to achieve a wider range of test velocities.

As can be seen in Figure 3, opposed smolder propagation is supported at substantially lower oxidizer flow rates in low gravity that in normal gravity. It should be noted that the pressure dependence of the buoyancy-induced heat losses is less than that of the buoyancy-induced mass flux, which explains why the difference in the critical mass flux between normal and microgravity for self-propagating smolder decreases as the pressure increases. Furthermore, these results appear to indicate that the effect of pressure on transport is dominant over its effect on chemical kinetics. In microgravity, where there is no buoyancy, the effect of pressure on the smolder velocity is weak ($\sim P^{1/3}$), and the smolder velocity is proportional to the oxidizer mass flux. In addition, in normal gravity for the same pressure and consequently the same buoyant heat losses, the smolder velocity is proportional to the oxidizer-mass flux in natural and forced flow smolder.

CONCLUDING REMARKS

A comparison of the tests conducted in normal- and microgravity indicates that there is a critical oxidizer mass flux to attain a self-propagating smolder reaction, and that this critical mass flux is significantly smaller in microgravity than in normal gravity. This finding has important implications from the point of view of fire safety in a space-based environment, since smolder can be initiated at lower oxygen concentrations or mass flows than in normal gravity. Since buoyant heat losses are the primary reason for these results, the quantitative differences are a function of the sample size, decreasing as the sample size increases. A comparison of only smolder propagation velocities ignores differences in reaction temperatures, in the extent of reaction and/or char conversion, conductive and/or forced convection heat losses. Examination of these effects is ongoing.

Table 1 Microgravity Experiment Results Summary

Forced Air velocity	Smolder Velocity	Smolder Temp	Igniter Power	Ignition Duration
(mm/s)	(mm/s)	°C	Watts (avg.)	s
1	0.10	385	70	1000
2	0.16	410	70	1000
3	0.17	421	90	600

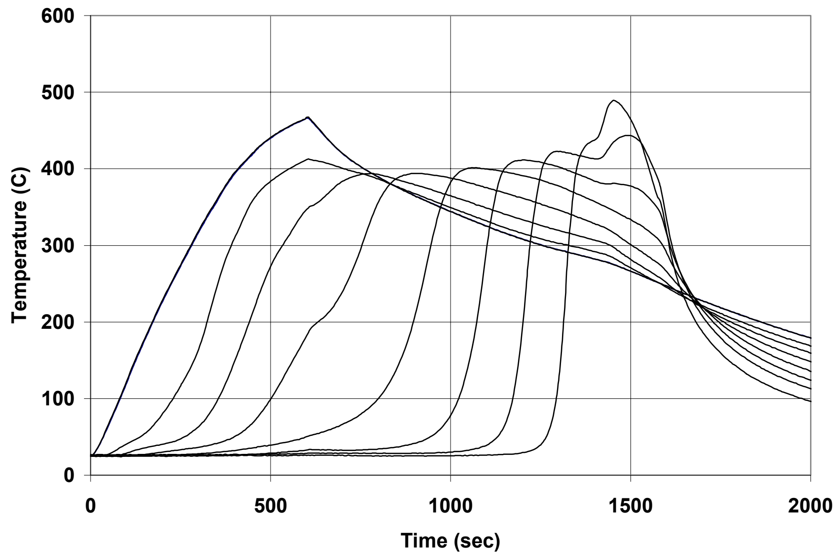

Figure 1: Temperature traces for the 3 mm/s opposed flow microgravity case. Temperature traces are along the sample axis at the following distances (mm) from the igniter (from left to right) 0, 12.5, 32.5, 52.5, 72.5, 92.5, 112.5, 132.5.

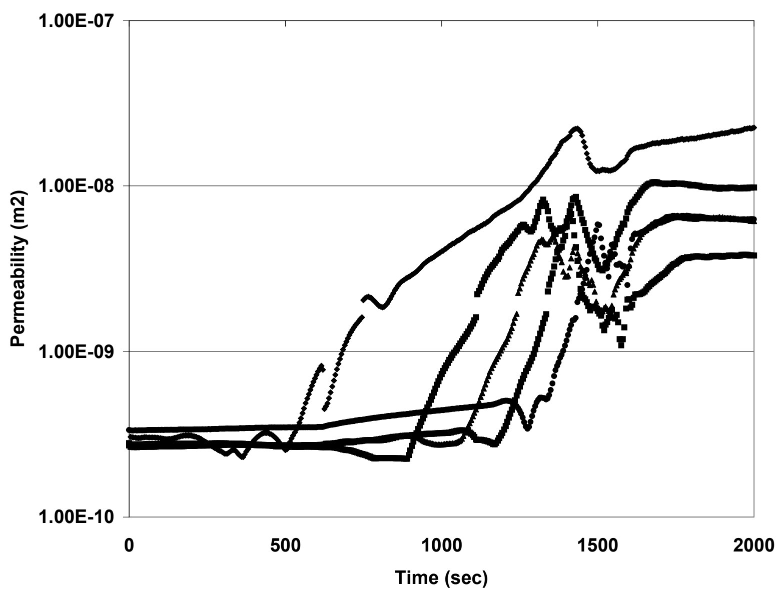

Figure 2: Permeability traces from the UIS for the 3 mm/s opposed flow microgravity case. Traces are line-of site across the sample axis at the following distances (mm) from the igniter (from left to right) 0, 25, 60, 80, 100, 120.

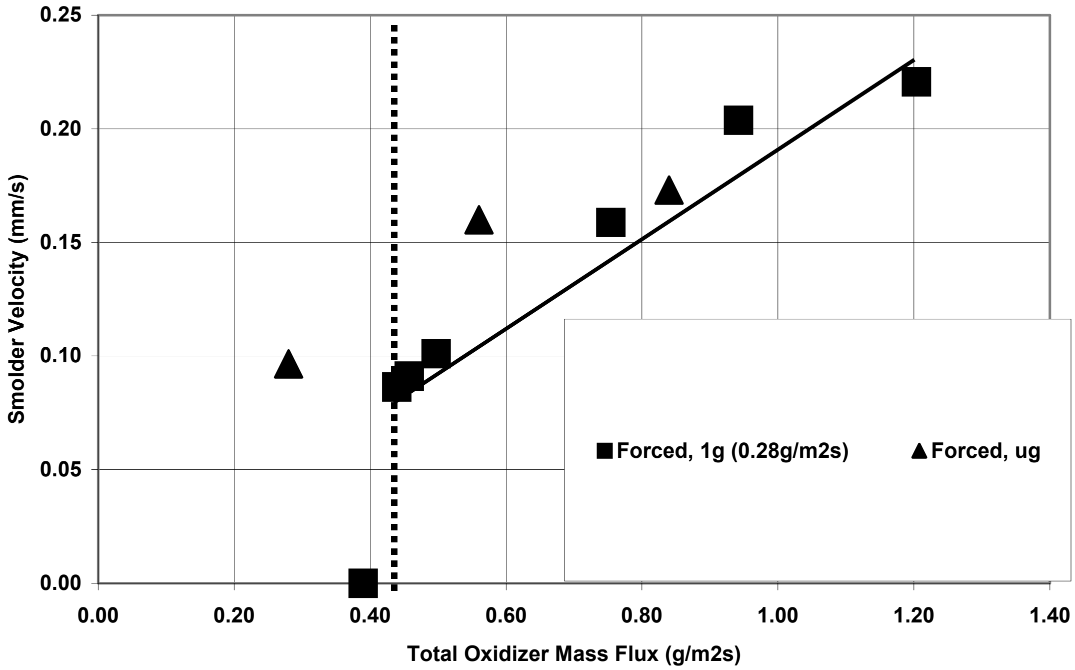

Figure 3: Smolder velocity versus mass flow rate of oxidizer for opposed forced flow smolder in normal- and microgravity.

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